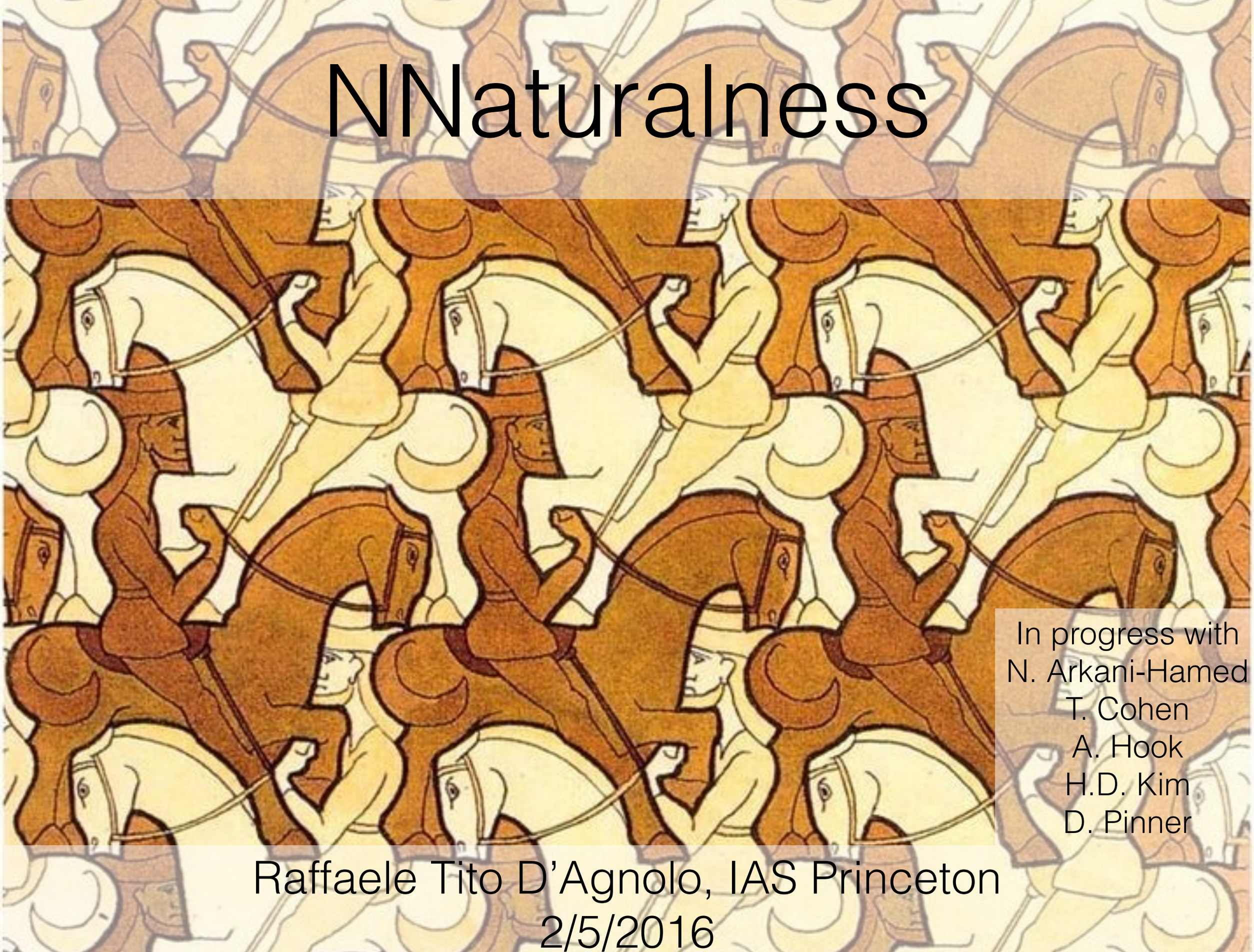
NNaturalness



In progress with
N. Arkani-Hamed
T. Cohen
A. Hook
H.D. Kim
D. Pinner

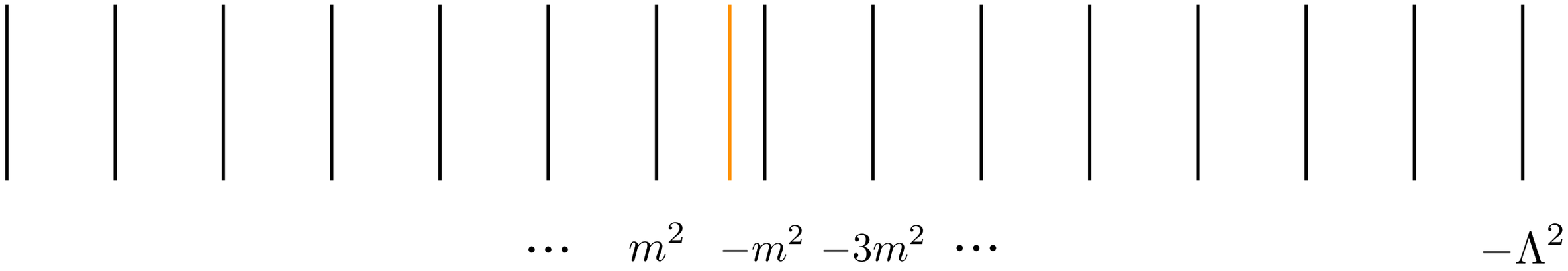
Raffaele Tito D'Agnolo, IAS Princeton

2/5/2016

NNATURALNESS

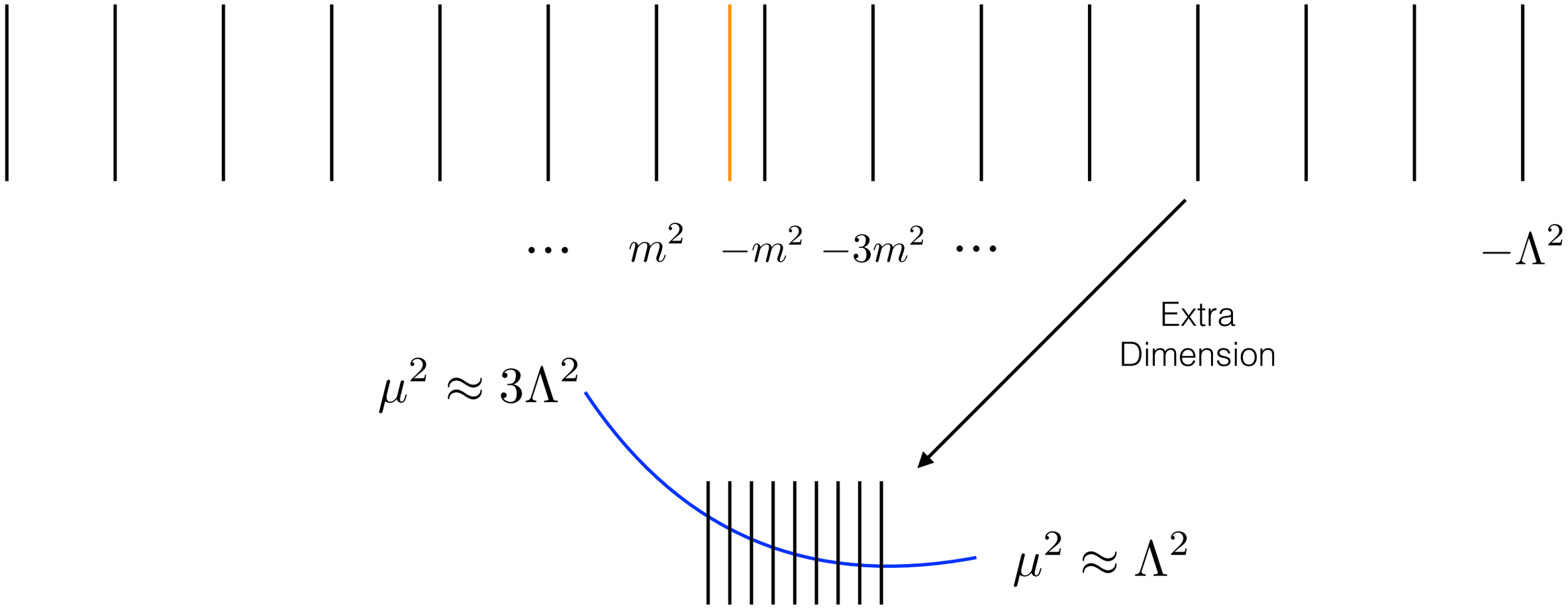
- NO FINE-TUNING OF THE HIGGS MASS
- NO NEW PARTICLES AT THE LHC
- VERY DISTINCT COSMOLOGICAL SIGNATURES

N COPIES

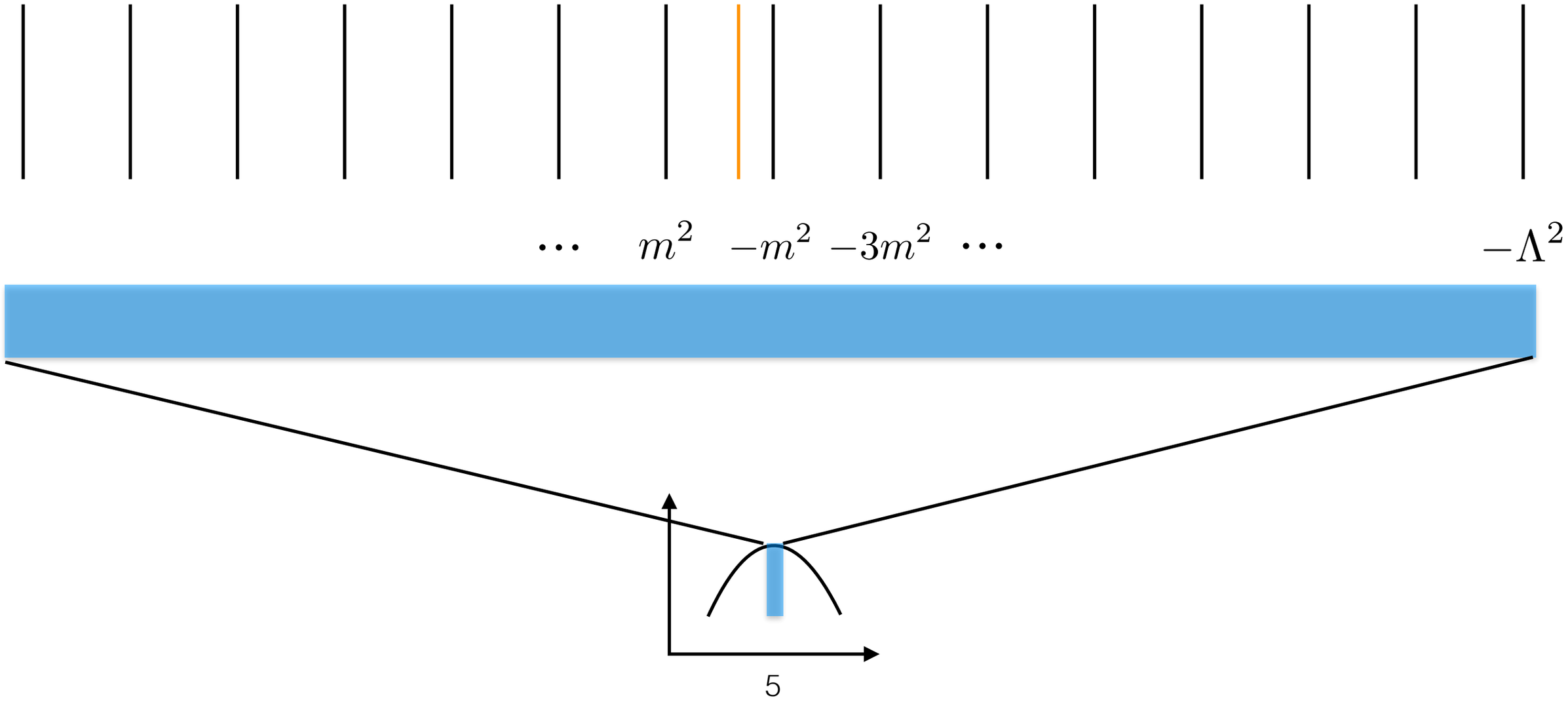


$$\Lambda^2 \sim m^2 N$$

N COPIES


$\cdots \quad m^2 \quad -m^2 \quad -3m^2 \quad \cdots$
$-\Lambda^2$
Extra
Dimension
$\mu^2 \approx 3\Lambda^2$
$\mu^2 \approx \Lambda^2$

N COPIES



THE SCALES

M_{Pl}

$\Lambda \sim m_h \sqrt{N}$

m_h

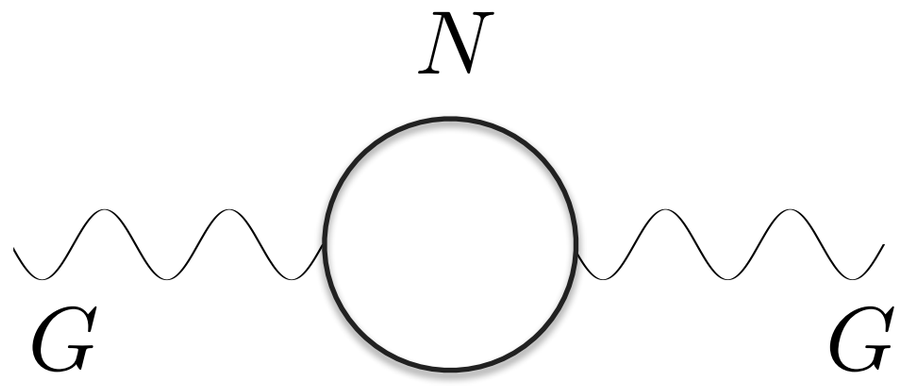
THE SCALES

M_{Pl}

$\Lambda_G \sim M_{Pl}/\sqrt{N}$

$\Lambda \sim m_h\sqrt{N}$

m_h



A PARTIAL SOLUTION

M_{Pl}

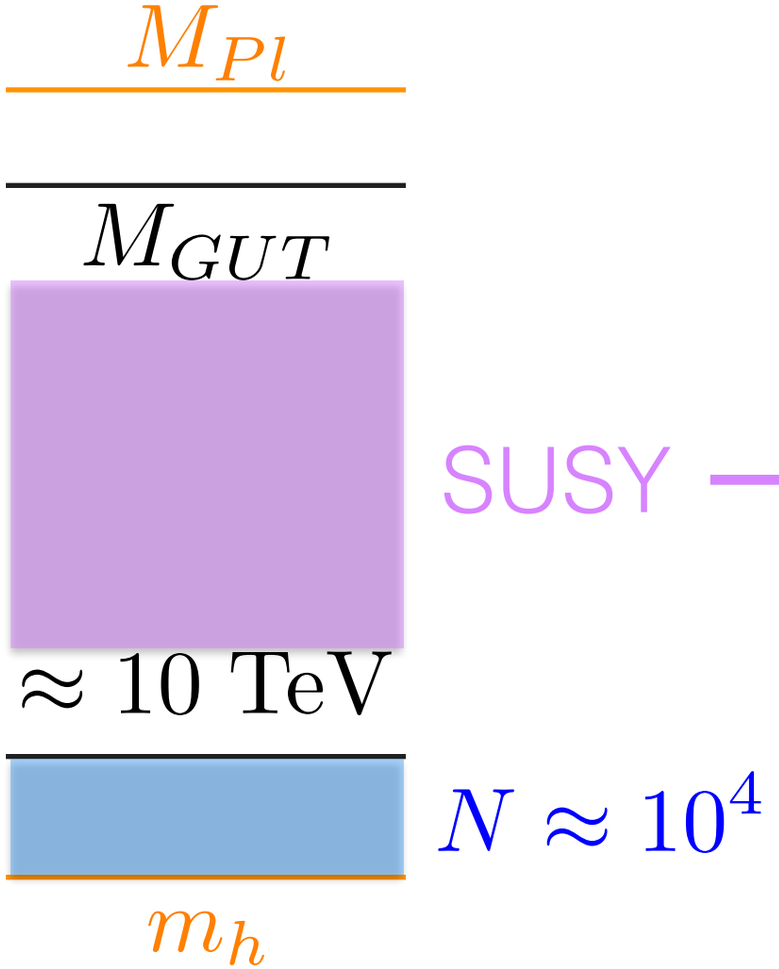
$\Lambda_G \sim M_{GUT}$

$N \approx 10^4$

$\Lambda \sim 10$ TeV

m_h

SUSY AT FUTURE COLLIDERS



- Unification
- Dark Matter
- Flavor/CP Signals
- Higgs at 125 GeV with no effort (Gauge mediation)

A FULL SOLUTION

M_{Pl}

$\Lambda_G \approx \Lambda \approx 10^{10}$ GeV $\qquad N \approx 10^{16}$

m_h

N COPIES

ALL THE COPIES ARE IN THE SAME VACUUM.
NOT A MULTIVERSE.

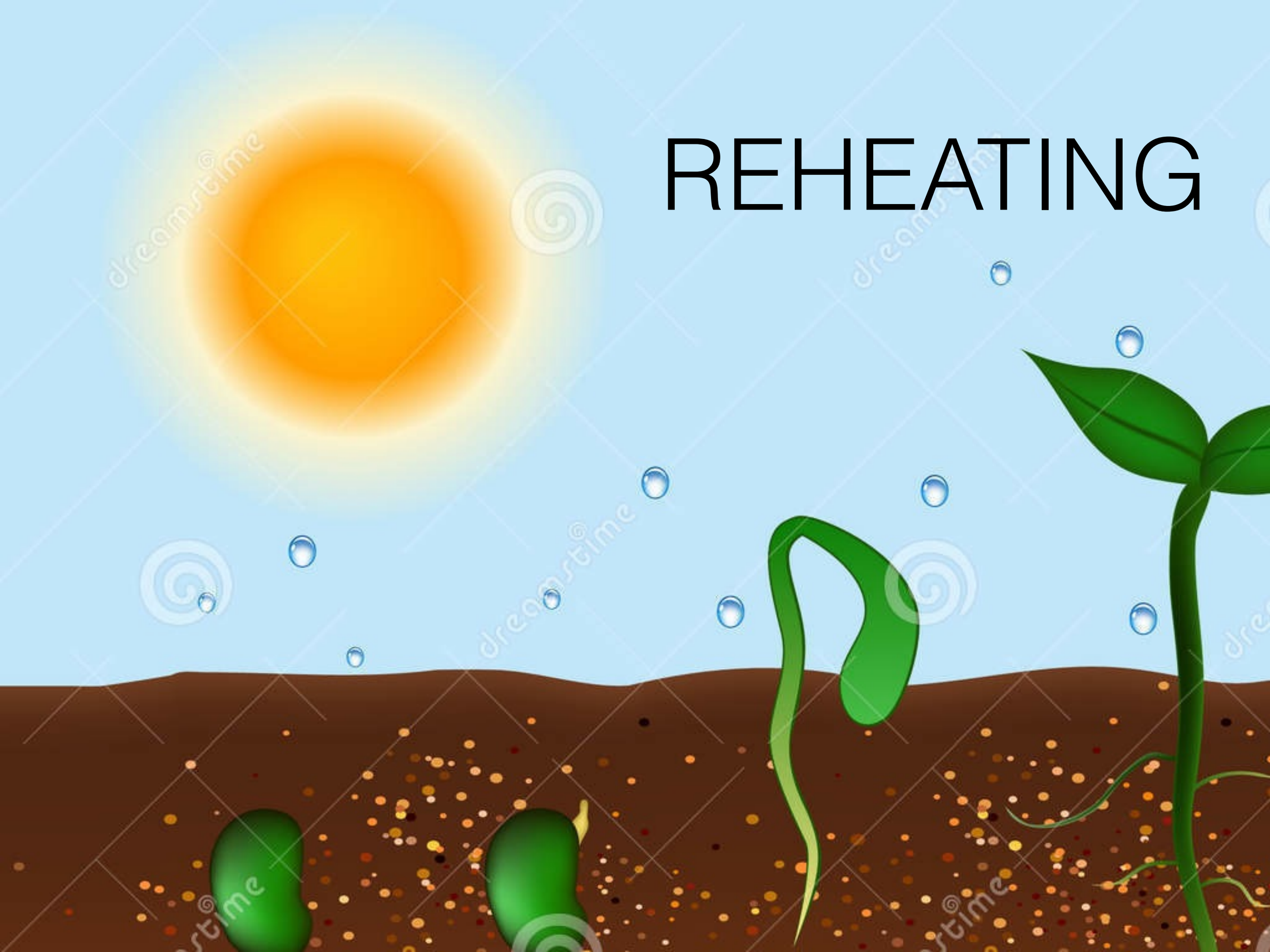
$m_h^2 < 0$

- Massless photons
- W, Z and fermion masses scale with v
- Neutrino masses grow as v (Dirac) or v^2 (Majorana)

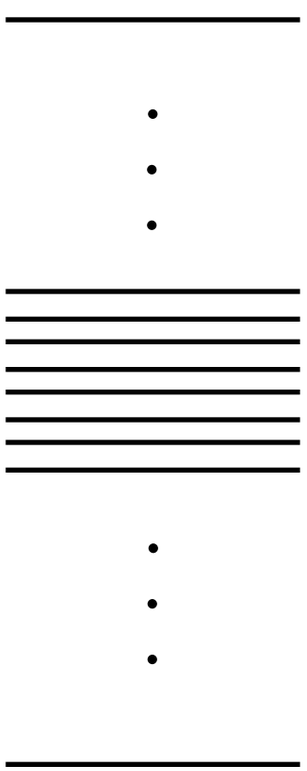
$m_h^2 > 0$

- Massless photons
- Nearly massless fermions
- W, Z at the QCD scale
- No baryons

REHEATING



REHEATON



Λ

m_h

ϕ, S

SCALAR

$$a\phi|H_i|^2$$

FERMION

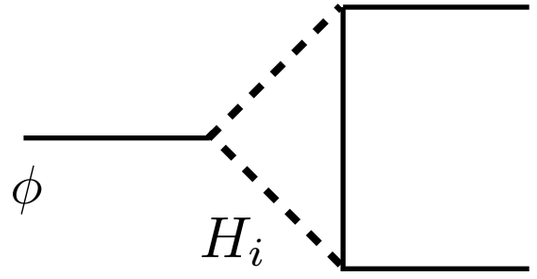
$$\lambda S l_i H_i$$

SCALAR REHEATON

SCALAR

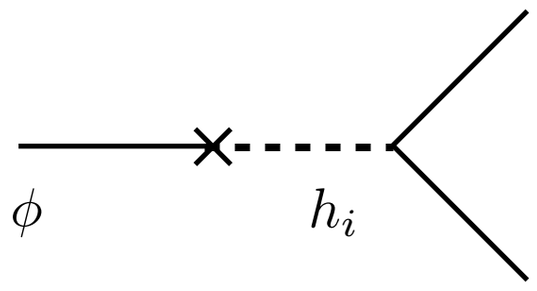
$$a\phi|H_i|^2$$

$m_h^2 > 0$



$$\frac{a}{m_{h_i}^2}\phi\bar{\psi}\gamma^\mu\partial_\mu\psi \qquad \Gamma \sim \frac{1}{m_{h_i}^4}$$

$m_h^2 < 0$

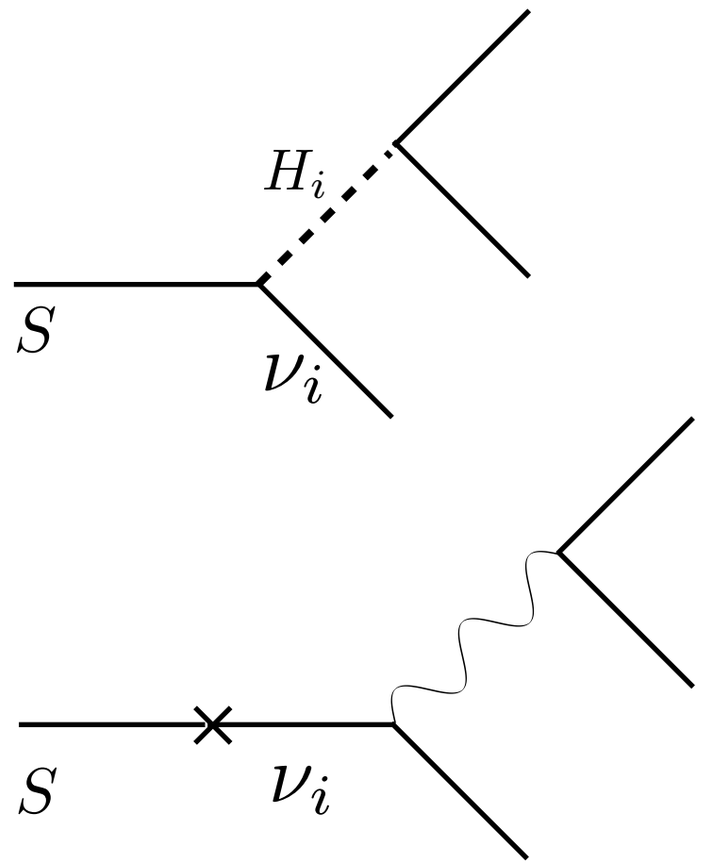


$$\frac{a}{m_{h_i}}\phi\bar{\psi}\psi \qquad \Gamma \sim \frac{1}{m_{h_i}^2}$$

FERMIONIC REHEATON

FERMION

$$\lambda S l_i H_i$$



$$m_h^2 > 0$$

$$\Gamma \sim \frac{1}{m_{h_i}^4}$$

$$m_h^2 < 0$$

$$\Gamma \sim \frac{1}{m_{h_i}^2}$$

L4

In the simple fermionic model: $N \lesssim 10^3$ Neutrino overclosure, …

$$\mathcal{L}_{L_4} \supset \mathcal{L}_{\rm mix} + \mathcal{L}_Y + \mathcal{L}_M \,,$$

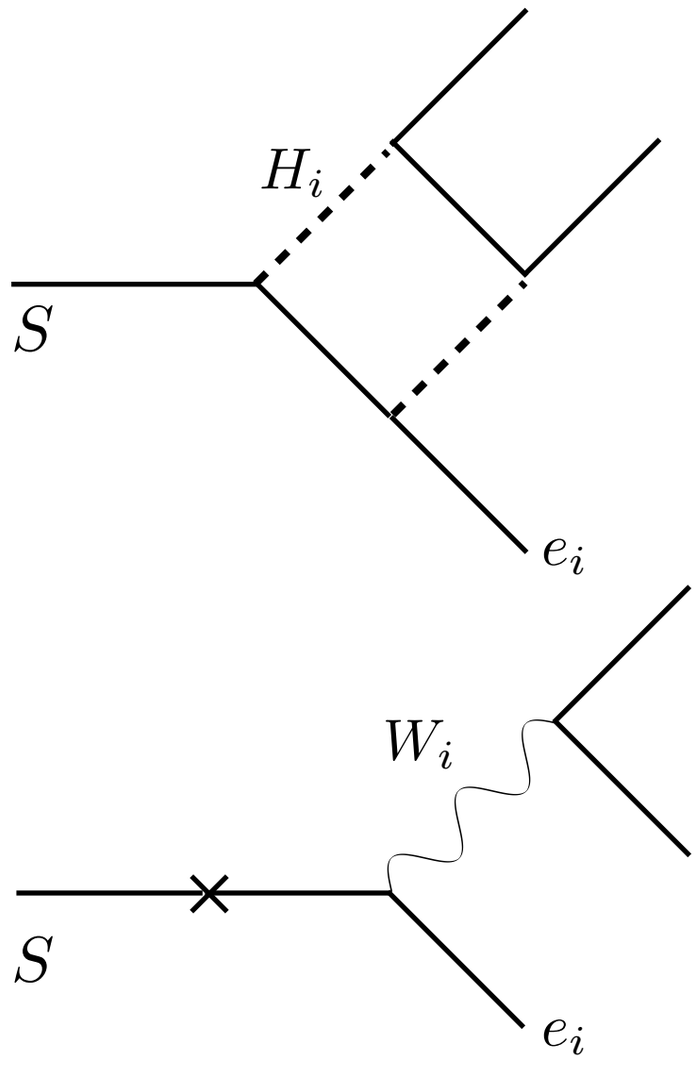
$$\mathcal{L}_{\rm mix} = -\lambda\, S^c \sum_i \left(L_4\, H\right)_i - \mu_E \sum_i \left(e^c\, E\right)_i \,,$$

$$\mathcal{L}_Y = -\sum_i \left[Y_E \left(H^\dagger\, L_4\, E_4^c\right)_i + Y_E^c \left(H\, L_4^c\, E_4\right)_i + Y_N \left(H\, L_4\, N_4^c\right)_i + Y_N^c \left(H^\dagger\, L_4^c\, N_4\right)_i \right] ,$$

$$\mathcal{L}_M = -\sum_i \left[M_E \left(E_4^c\, E_4\right)_i + M_L \left(L_4^c\, L_4\right)_i + M_N \left(N_4^c\, N_4\right)_i \right] - m_S\, S\, S^c \,,$$

L4

$m_h^2 > 0$

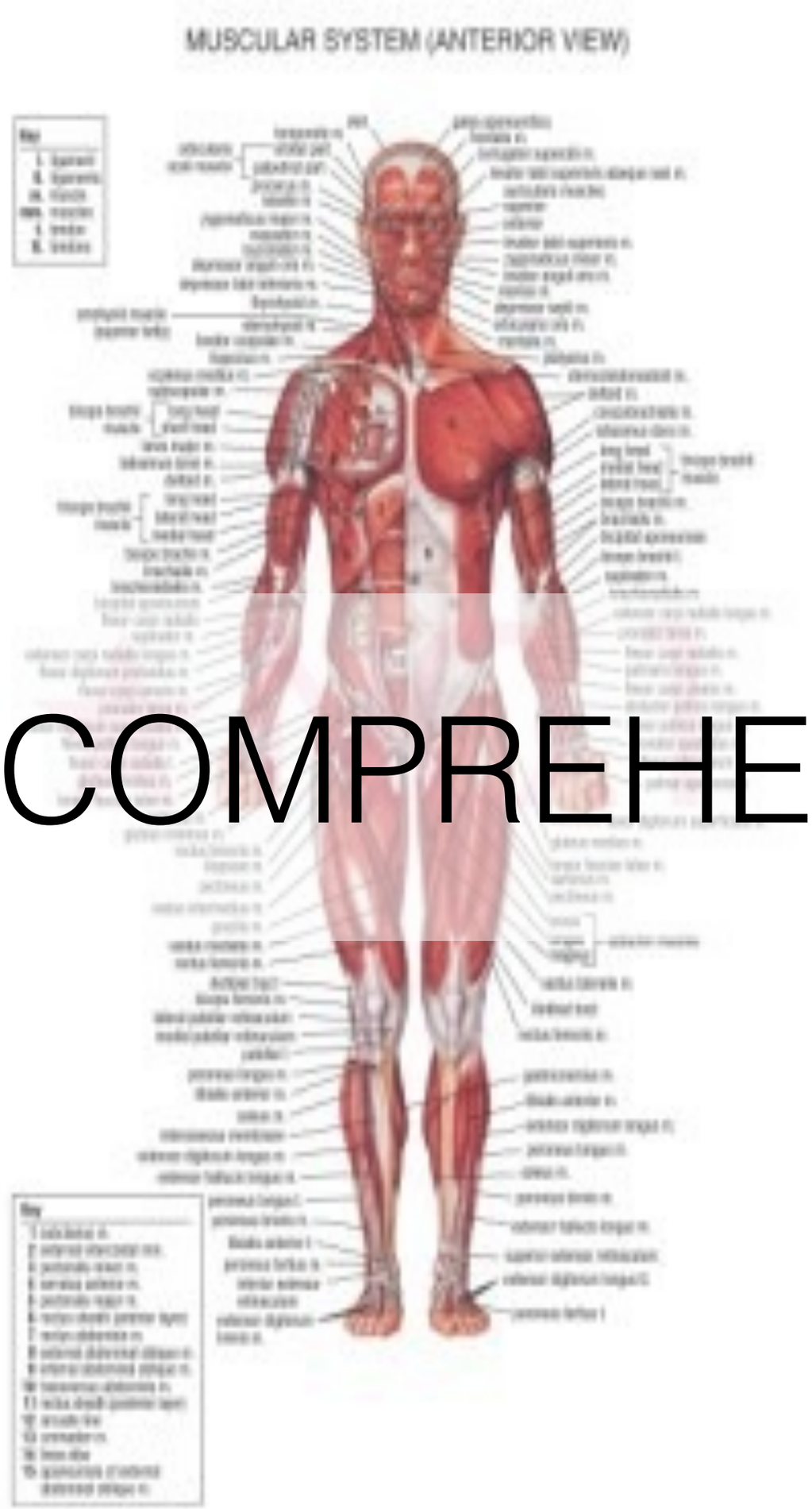


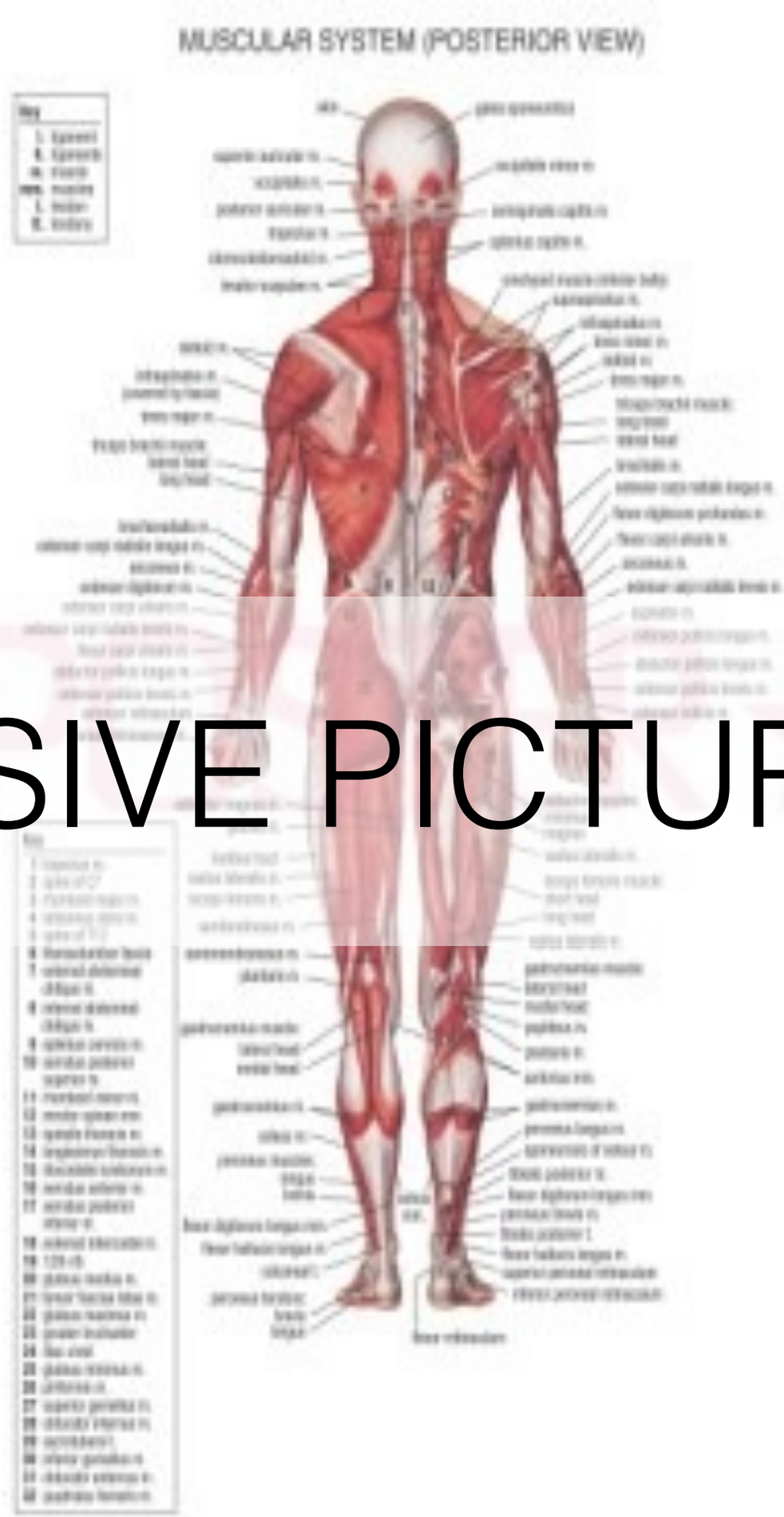
$$\Gamma \sim \left(\frac{y_t y_b}{16\pi^2}\right)^2 \frac{1}{m_{h_i}^8}$$

$m_h^2 < 0$

$$\Gamma \sim \text{const.} \quad v_i < M_V$$

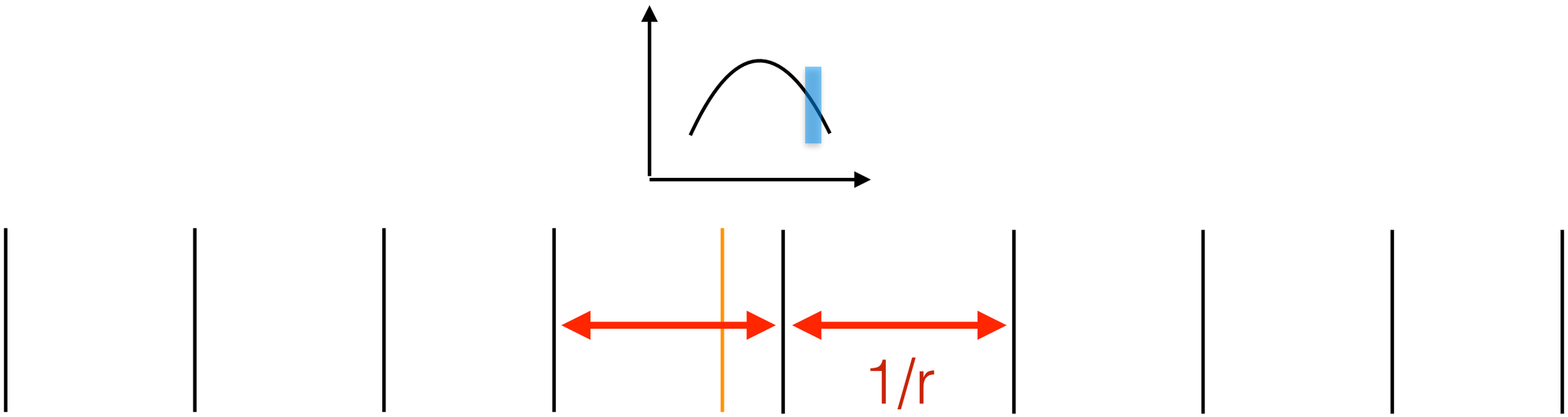
$$\Gamma \sim \frac{1}{m_{h_i}^8} \quad v_i > M_V$$





A COMPREHENSIVE PICTURE

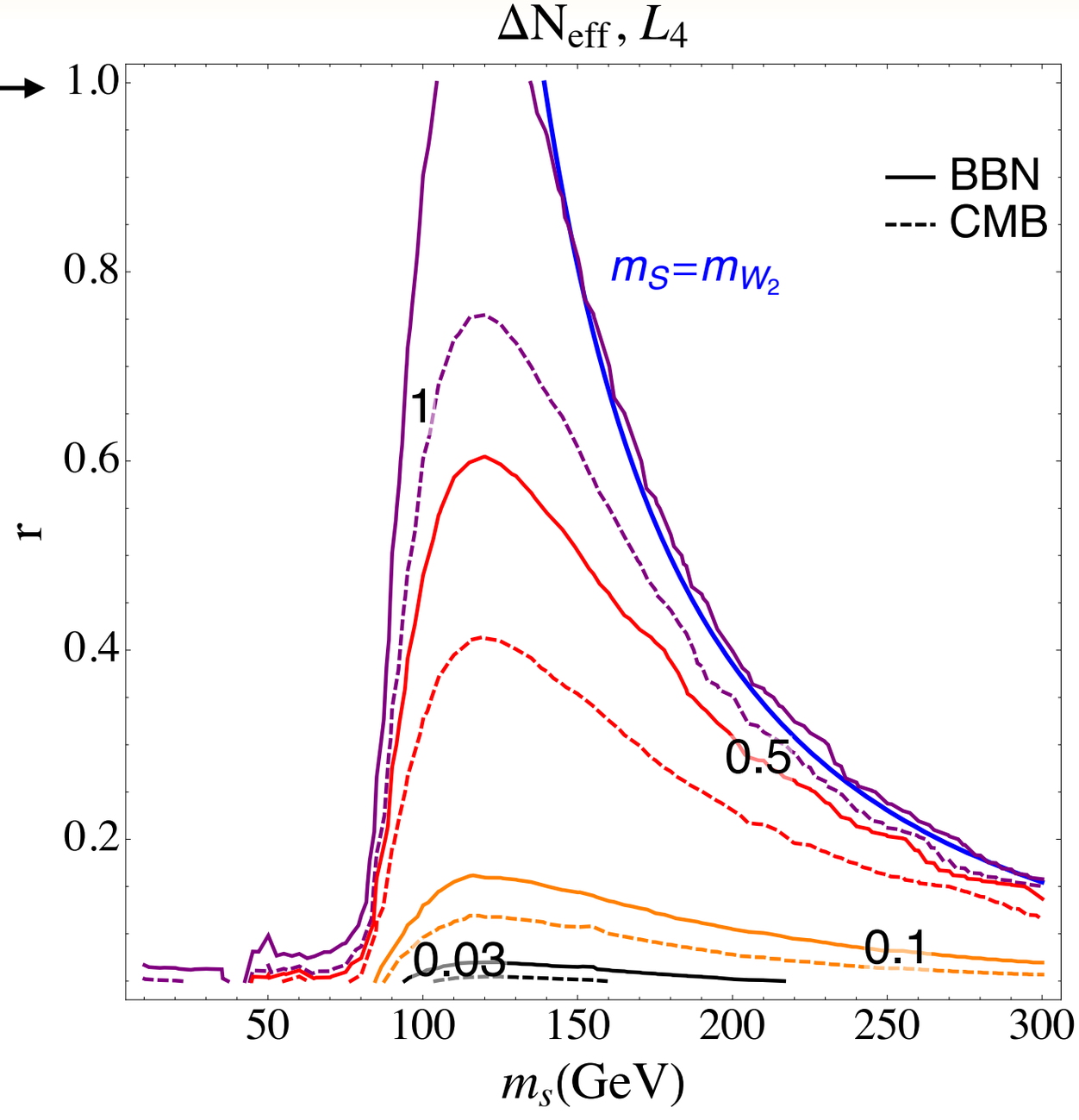
THE BOTTOM OF THE SPECTRUM



$$r \equiv \frac{2m_h^2}{\Delta m_h^2}$$

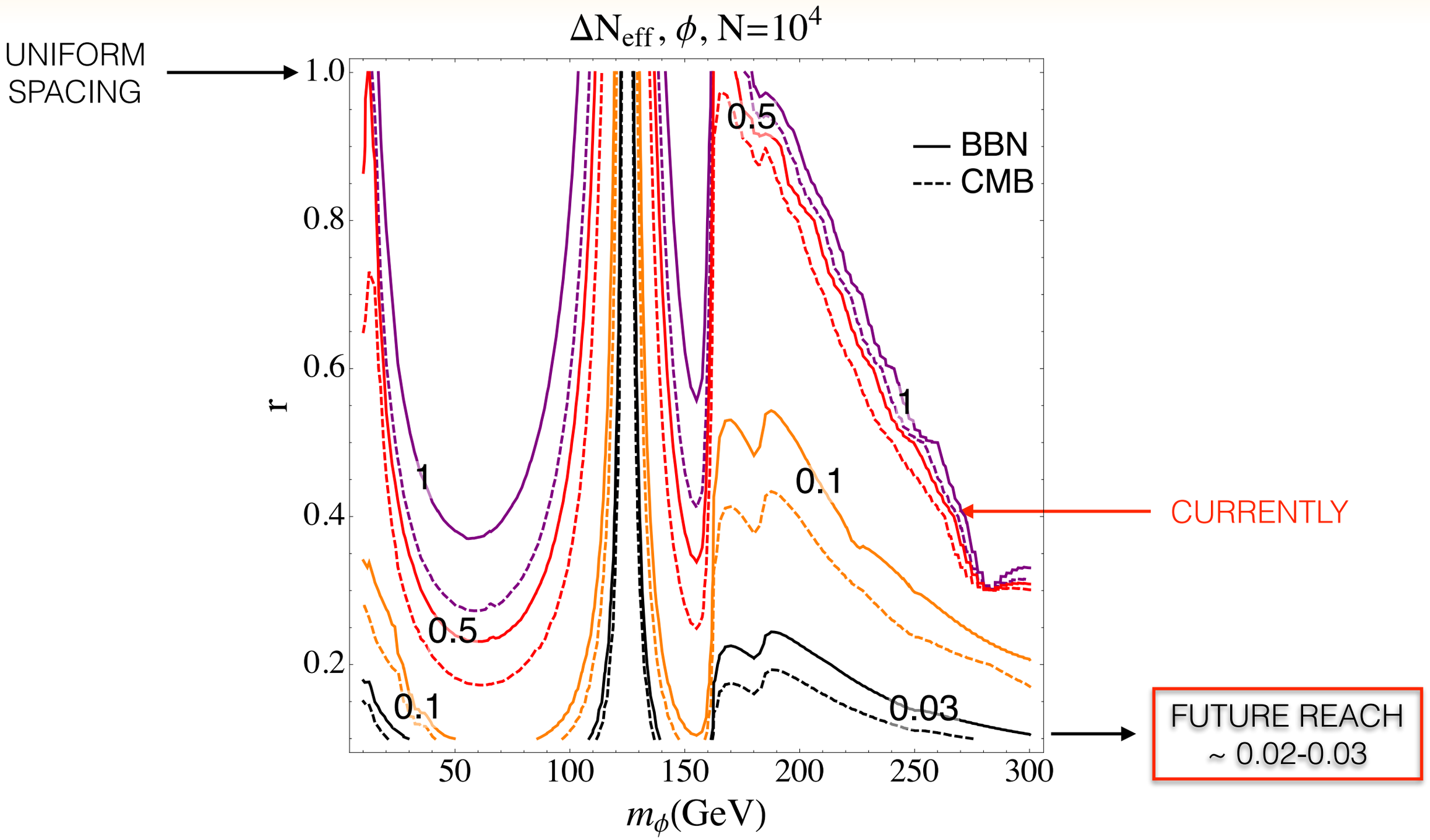
N_{eff}

UNIFORM SPACING →

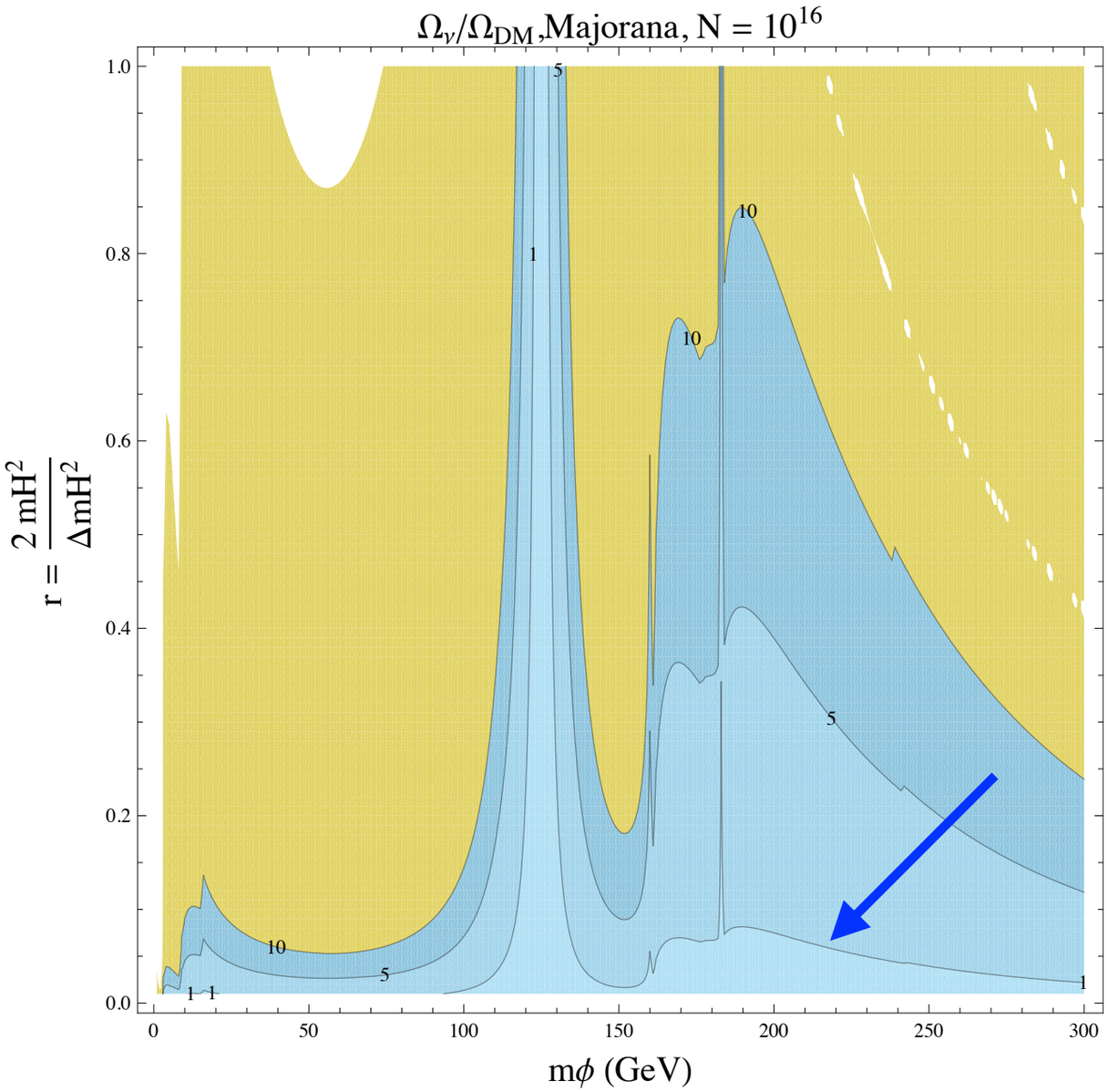


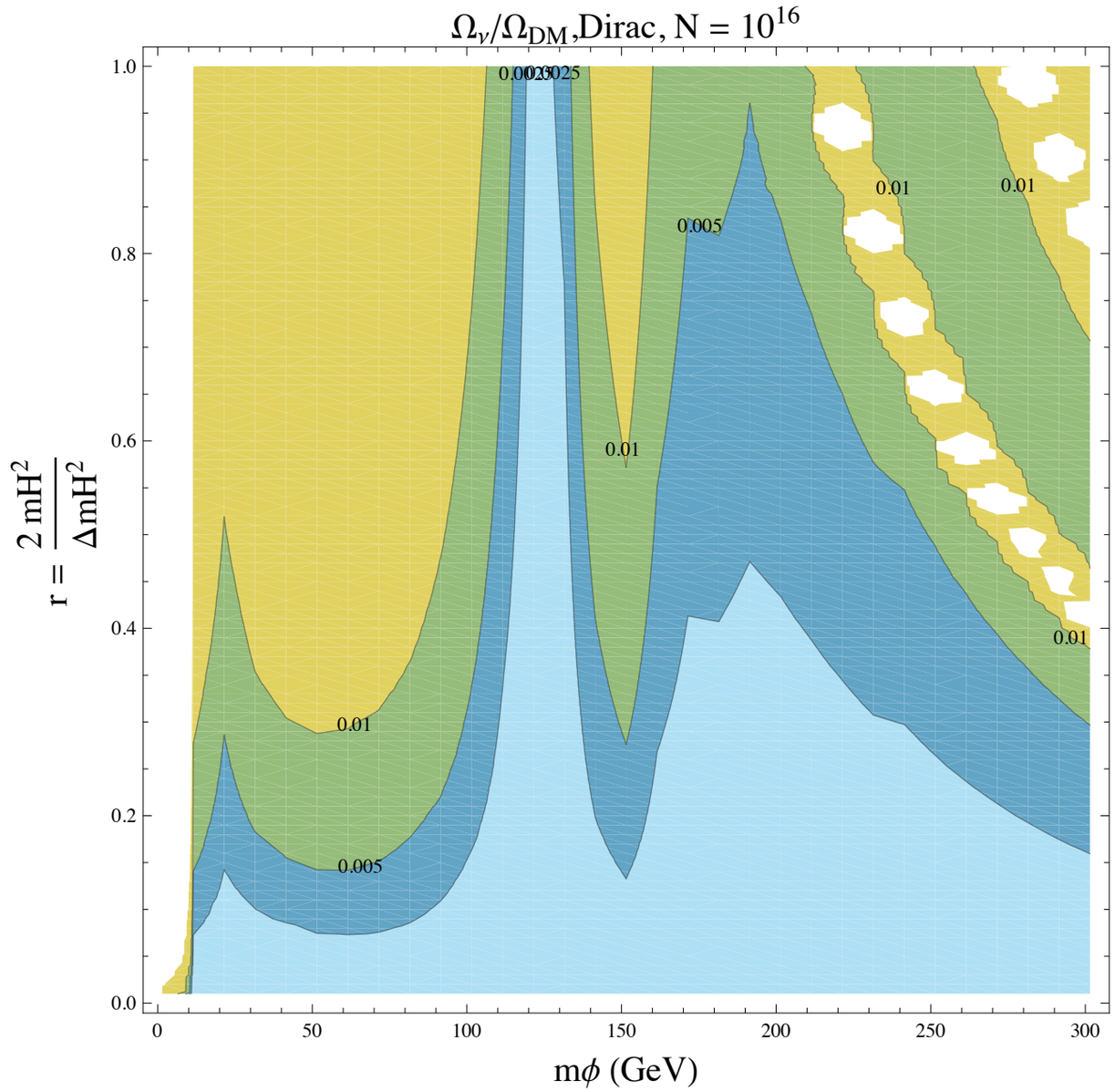
→ FUTURE REACH ~ 0.02-0.03

N_{eff}


ΔN_{eff}, ϕ, N=10^4
UNIFORM SPACING
1.0
0.8
0.6
0.4
0.2
r
50
100
150
200
250
300
m_ϕ(GeV)
BBN
CMB
1
0.5
0.1
0.03
CURRENTLY
FUTURE REACH
~ 0.02-0.03

NEUTRINO OVERCLOSURE





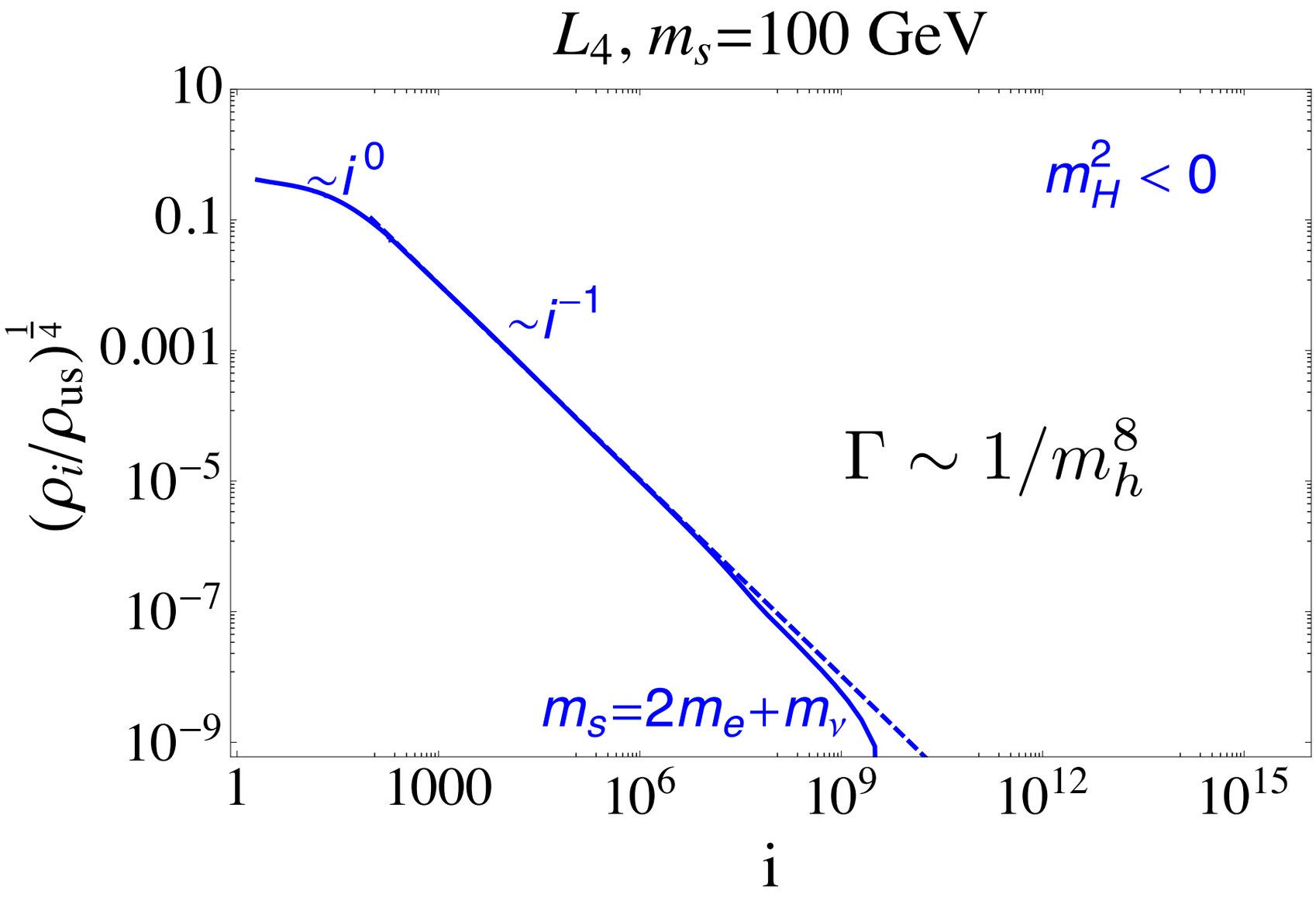
ELECTRON OVERCLOSURE

$$m_{e_i} \gg m_e$$

$$v_i \gg v \longrightarrow \sigma_{e_i} \sim \frac{\alpha^2}{m_{e_i}^2} \ll \sigma_e$$

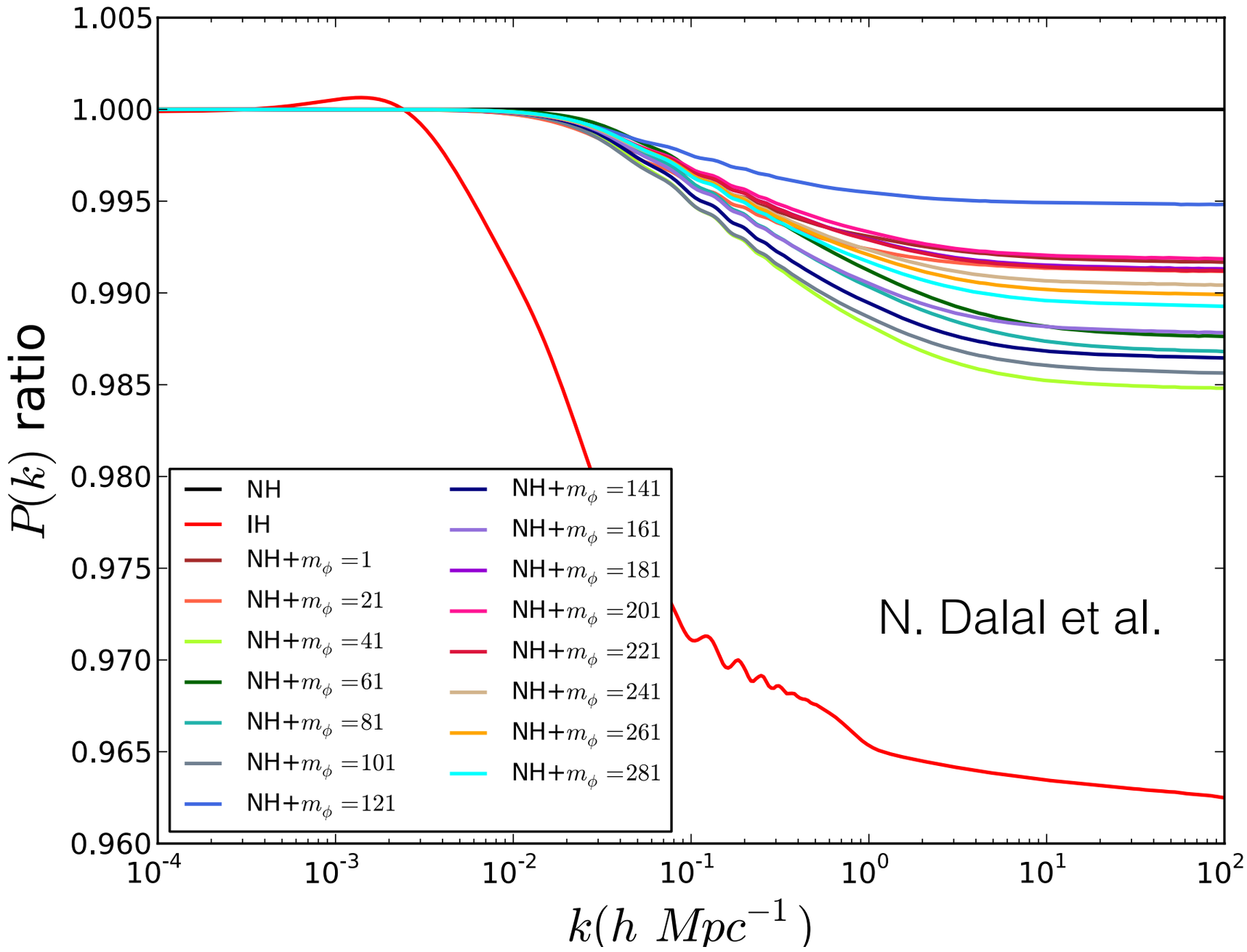
$$N_\phi \lesssim 10^5$$

OVERCLOSURE IN L4



$N_{L_4} \to 10^{16}$

NEUTRINO SIGNAL



LIFE, THE UNIVERSE AND EVERYTHING…

- ONE AXION SOLVES ALL STRONG CP PROBLEMS
  - $m_a = \frac{1}{f}\sum m_{\pi_i} f_{\pi_i} \frac{\sqrt{m_{u_i} m_{d_i}}}{m_{u_i} + m_{d_i}} \sim N^{3/4} \frac{\Lambda_{QCD}^2}{f}$
- DARK MATTER IS EASY
  - NEUTRALINOS, NEUTRINOS IN THE OTHER SECTORS, SUPERSYMMETRIC PARTNER OF THE REHEATON, AXION, …
- BARYOGENESIS IS NOT COMPLETELY TRIVIAL
  - MAXIMAL REHEATING TEMPERATURE
  - OVERCLOSURE FROM PROTONS

LHC RUN II

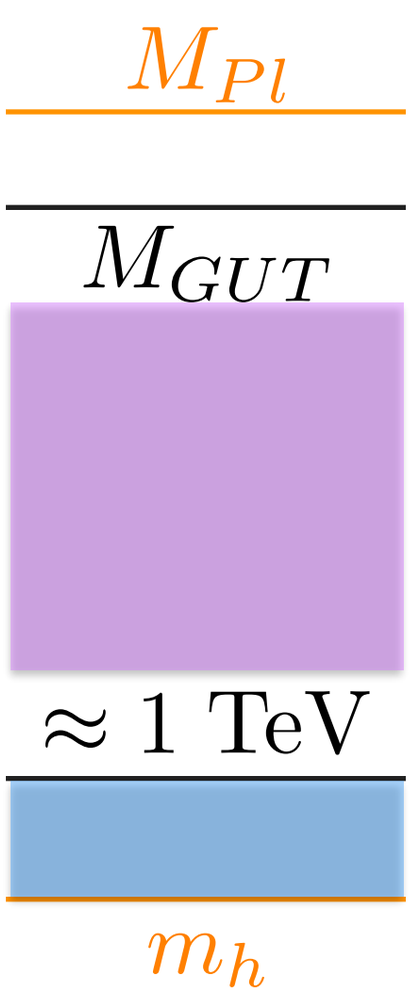
WHAT IF THE LHC FINDS SUSY?

STEP 1

STEP 2

IF EWSB IS ESSENTIALLY NATURAL, A 1-10% TUNING IS HARD TO UNDERSTAND

SUSY AT THE LHC



- Unification
- Dark Matter
- Flavor/CP signals

SUMMARY OF SIGNALS

- FUTURE CMB EXPERIMENTS
  - Neff
  - NEUTRINO FRACTION OF DARK MATTER
- HEAVY AXION
- SUSY AT FUTURE COLLIDERS

THE OTHER KIDS IN THE PLAYGROUND

SUSY

SOFTLY BROKEN

MEDIATED TO US

MU PROBLEM

…

RELAXION

COSMOLOGY

SMOKING GUN OBSERVABLES ?

NNATURALNESS

ADD and Dvali-Redi

N~10^32

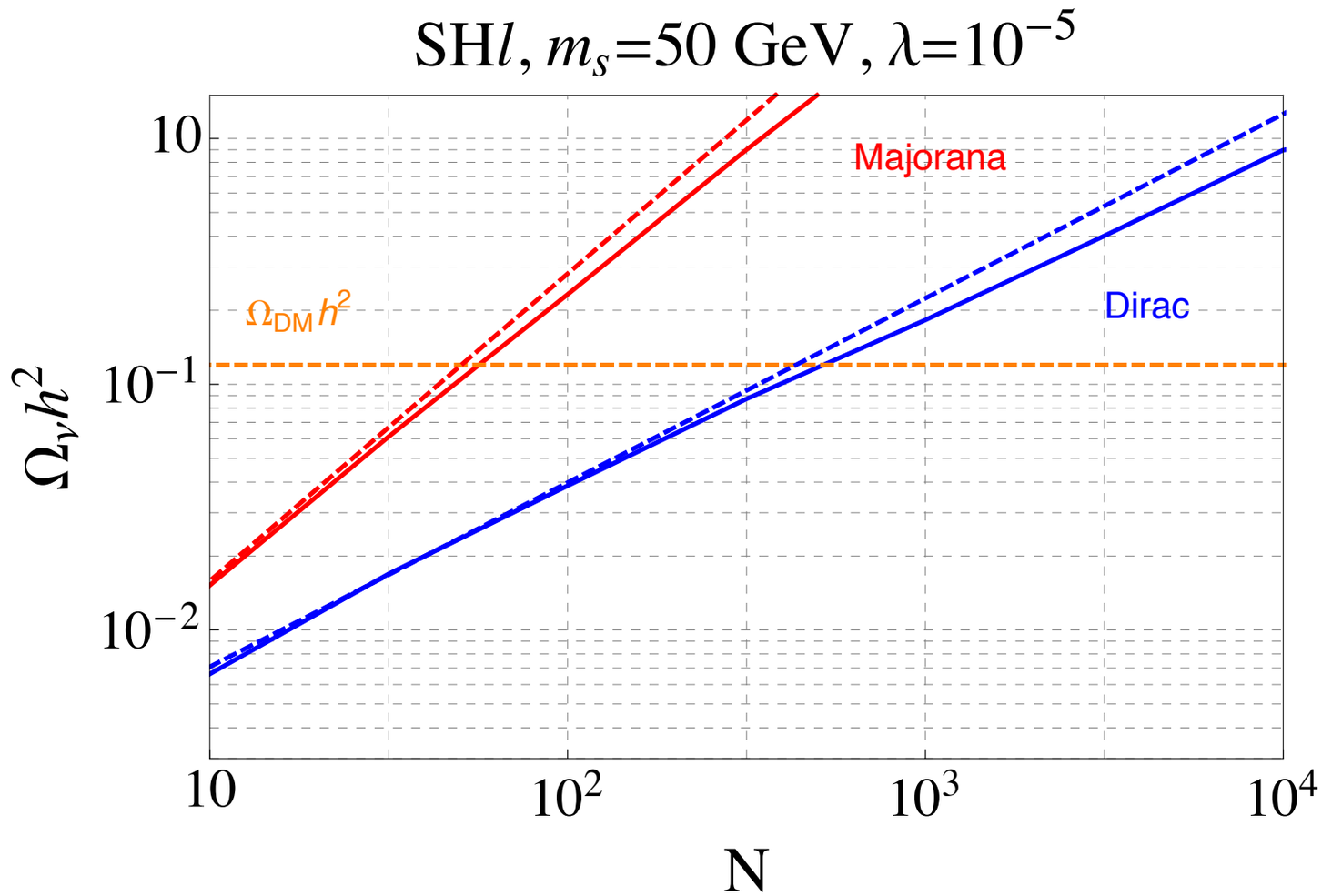
STRONG GRAVITY AT THE LHC

CONCLUSION

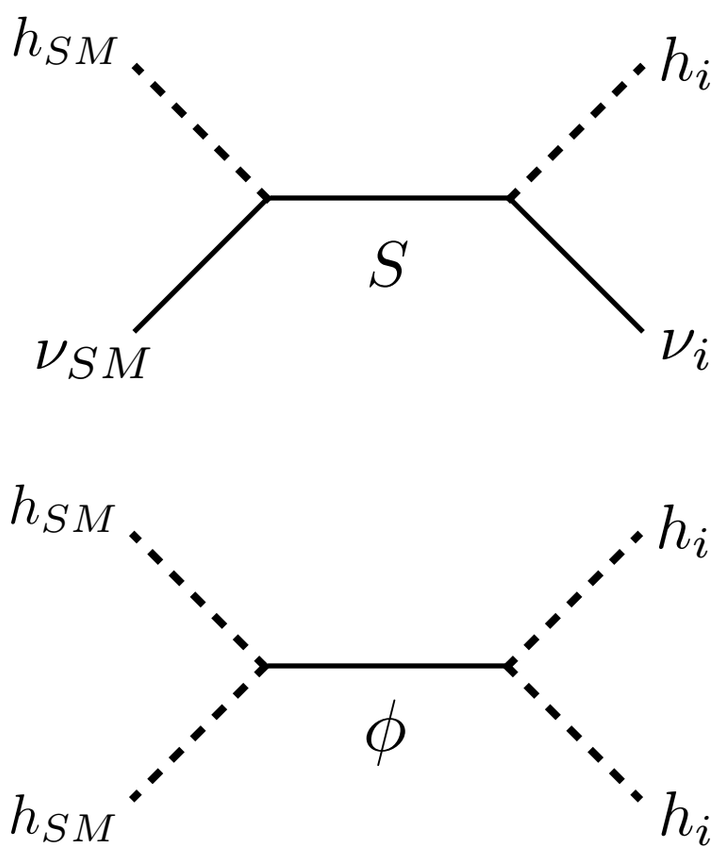
- THE LARGE NUMBER OF COPIES IS HARD TO ACCEPT
- THE MECHANISM WORKS FOR REASONS THAT ARE CLOSELY RELATED TO THE HIERARCHY PROBLEM
- MANY EXPERIMENTS (USUALLY UNRELATED TO THE HIERARCHY PROBLEM) TO LOOK FORWARD TO
- PLENTY OF INTERESTING PHYSICS (STRUCTURE FORMATION, BARYOGENESIS, "MU PROBLEM", …) TO THINK ABOUT

BACKUP

NEUTRINO OVERCLOSURE

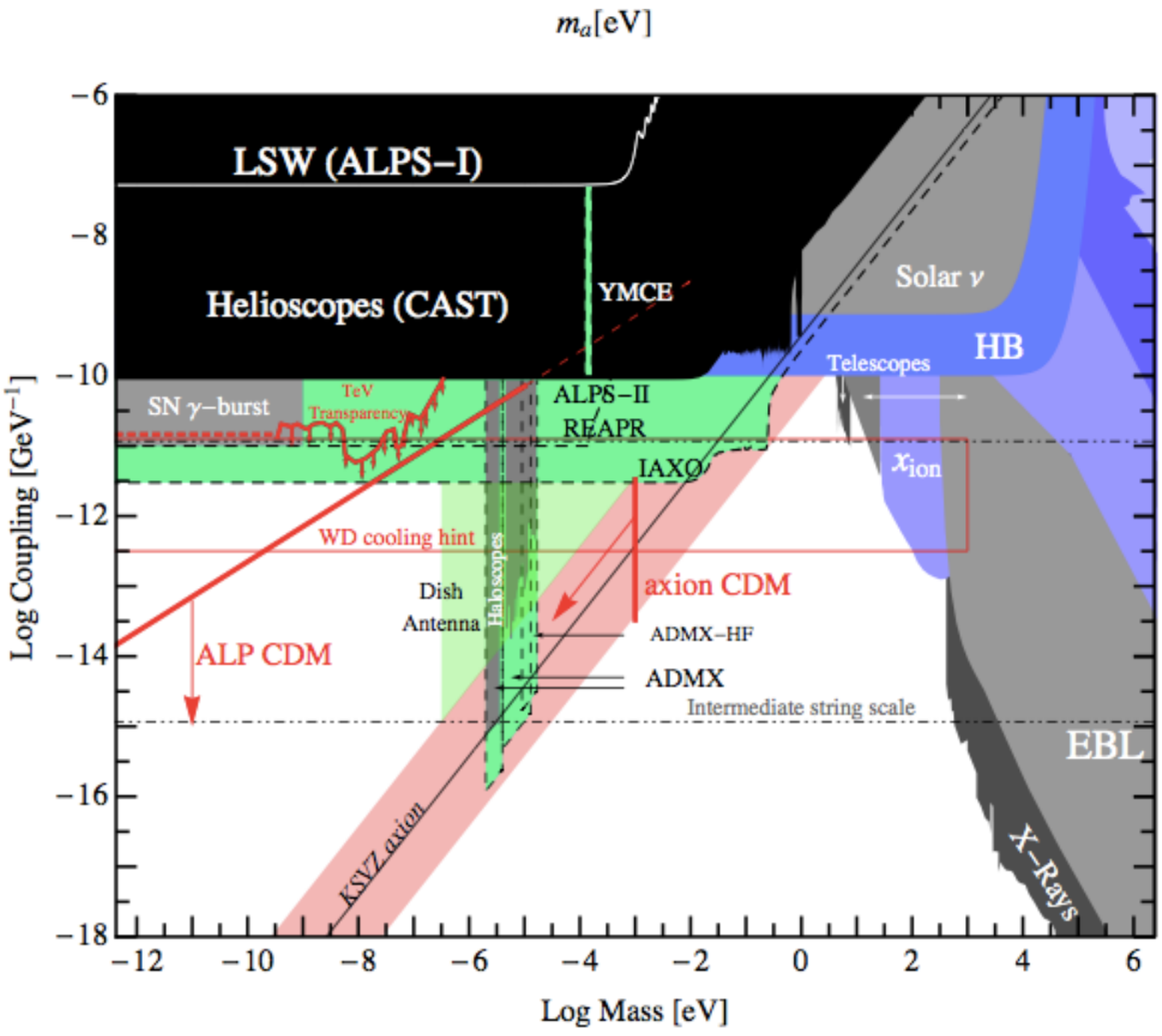


BOUNDS ON THE REHEAT TEMPERATURES



$$T_{RH} \lesssim 10 \text{ TeV}$$

AXION


m_a[eV]
LSW (ALPS–I)
Helioscopes (CAST)
YMCE
Solar ν
HB
Telescopes
SN γ–burst
TeV Transparency
ALPS–II
REAPR
IAXO
$x_{\rm ion}$
WD cooling hint
Dish Antenna
Haloscopes
axion CDM
ALP CDM
ADMX–HF
ADMX
Intermediate string scale
EBL
X–Rays
KSVZ axion
Log Coupling [GeV^{-1}]
Log Mass [eV]
−6
−8
−10
−12
−14
−16
−18
−12
−10
−8
−6
−4
−2
0
2
4
6

ONE AXION

- N COPIES = 1 STRONG CP PHASE
  - WITH SMALL CORRECTIONS FROM THE SOFT BREAKING OF THE Z_N SYMMETRY

- A SINGLE AXION SOLVES ALL CP PROBLEMS

$$m_a = \frac{1}{f} \sum m_{\pi_i} f_{\pi_i} \frac{\sqrt{m_{u_i} m_{d_i}}}{m_{u_i} + m_{d_i}} \sim N^{3/4} \frac{\Lambda_{QCD}^2}{f}$$

DARK MATTER

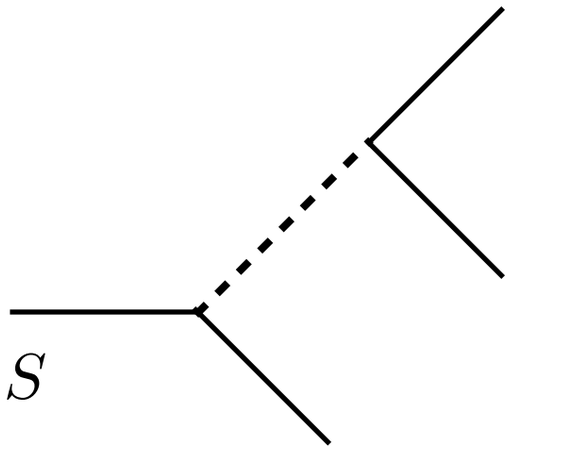
- NEUTRINOS FROM THE OTHER SECTORS
- NEUTRALINOS OF HIGH SCALE SUSY
- SUPERSYMMETRIC PARTNER OF THE REHEATON
- AXION
- …

BARYOGENESIS

- NOT COMPLETELY TRIVIAL
- MAXIMAL REHEATING TEMPERATURE
- OVERCLOSURE FROM PROTONS IN THE OTHER SECTORS

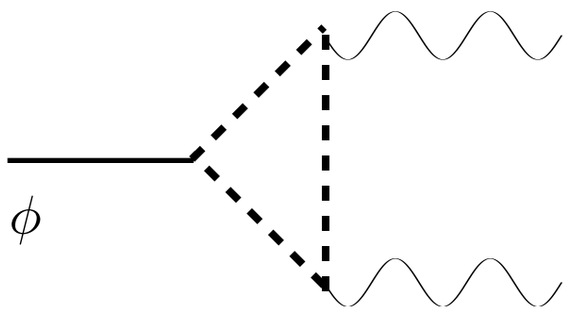
BARYOGENESIS

$$m_h \sim T^2$$



$$\sim \frac{1}{T^4}$$

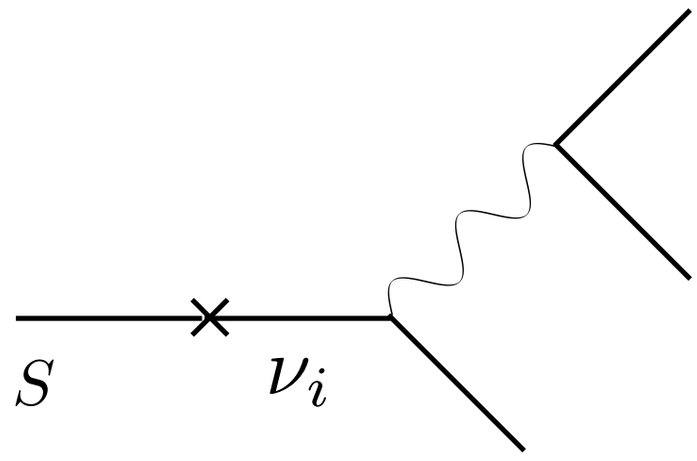
$$T_{RH} \lesssim m_{h2} \lesssim 200 \text{ GeV}$$



$$\sim \frac{a^2}{T^4}$$

BARYOGENESIS

SMALL ASYMMETRY IN S



SPHALERONS

ONLY A FEW SECTORS GET A BARYON RELIC ABUNDANCE

NNATURLANESS AT COLLIDERS

- IN PRINCIPLE EXCITING SIGNATURES
- RARE HIGGS AND Z DECAYS
- DIRECT PRODUCTION OF THE REHEATON
  - ITS INVISIBLE BR WOULD INCREASE WITH THE CM ENERGY!

NNATURLANESS AT COLLIDERS

$$T_{RH} \lesssim m_{h2} \lesssim 200 \text{ GeV} \longrightarrow \boxed{\lambda, a/m_h \lesssim 10^{-5} - 10^{-6}}$$

- NO SIGNALS AT A 100 TeV pp COLLIDER OR TLEP

LHC RUN II

WHAT IF THE LHC FINDS SUSY?

LHC RUN II

STEP 1

LHC RUN II

STEP 2

IF EWSB IS ESSENTIALLY NATURAL, 1-10% TUNING IS HARD TO UNDERSTAND

N COPIES